Energy dependence of detectors for 3D dosimetry of light ion beams

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Overview

Need for measuring absorbed dose

Characteristics of ideal 2D and 3D detectors

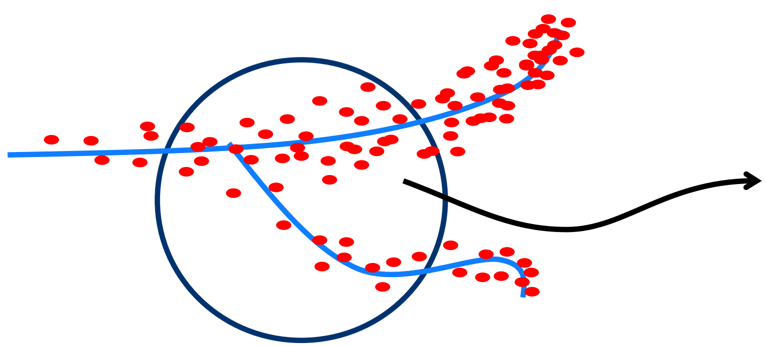
Energy dependence of detector response to absorbed dose

Absorbed dose versus fluence

Most of this conference: $\Phi, \dfrac{\partial\Phi}{\partial E}$ or $\dfrac{\partial^2\Phi}{\partial E \partial\theta}$

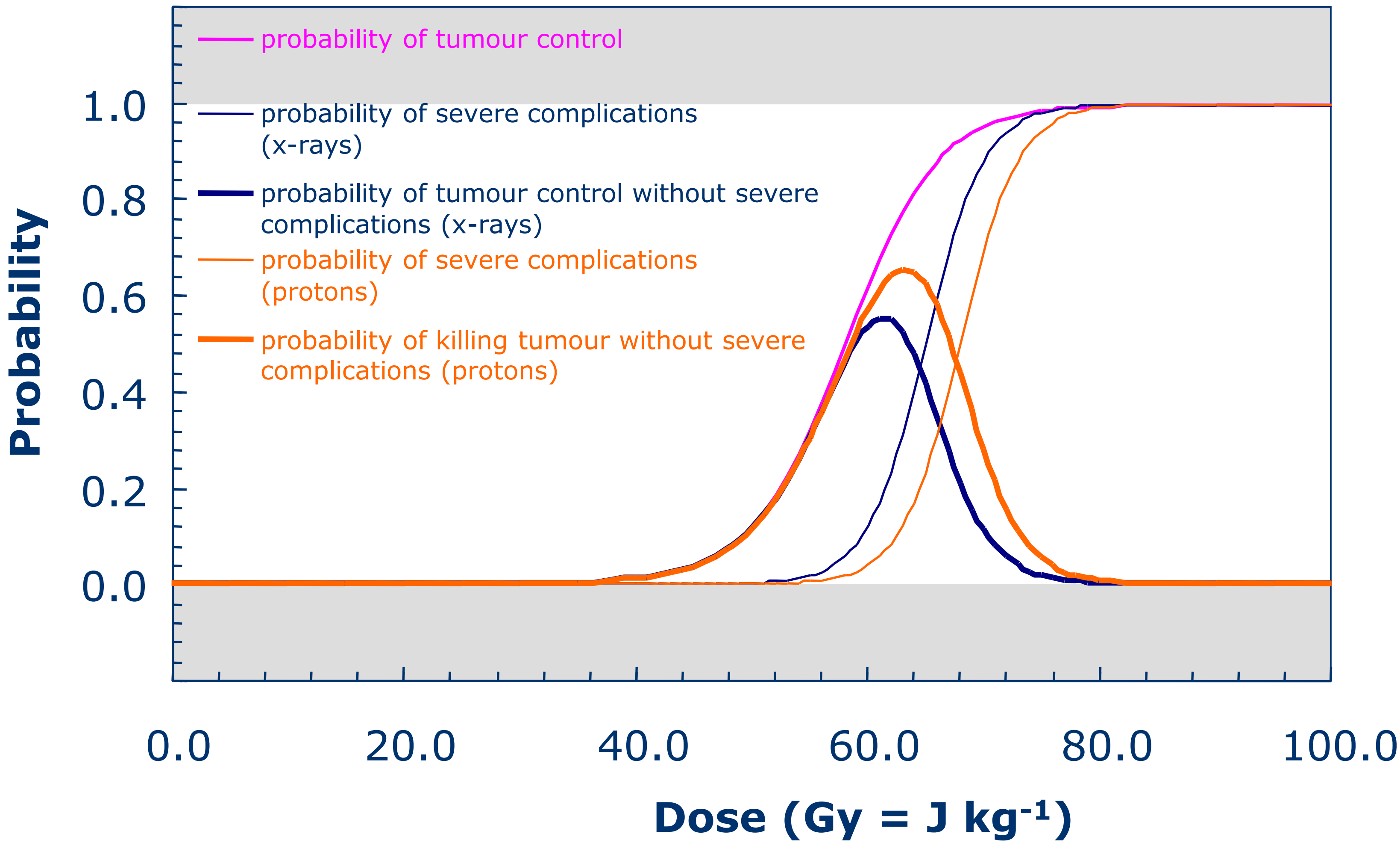
This presentation: $D_{med} = \dfrac{d\bar{\epsilon}}{dm}$

$\epsilon = \epsilon_{in} - \epsilon_{out} + \Delta Q =$ energy imparted



- thermalisation
- ionisation
- chemical states
- physical states

Need for accurate dosimetry



Need for measuring absorbed dose

At the cellular level:

- direct DNA damage: ionisation at nanoscale
- indirect DNA damage: ionisation at microscale
- other damage: tens of micrometers scale
- bystander effects: millimetre scale

For photons and electrons:

- biological effects ~ ionisation ~ absorbed dose

For protons and ions:

- biological effects ~ ionisation * w_i ~ absorbed dose * w_i * w_D

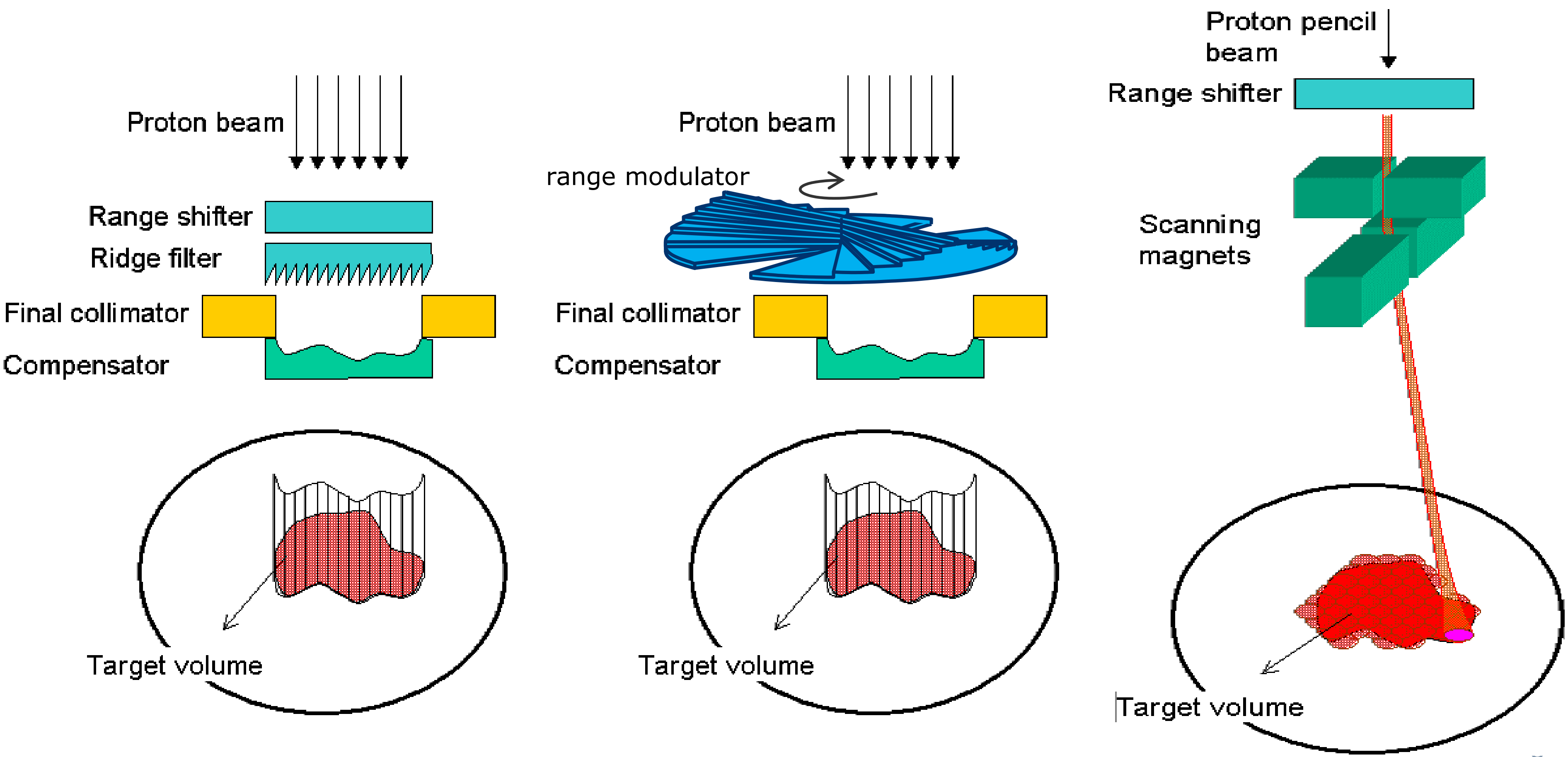
Need for 3D dosimetry

- Homogeneity
- Target coverage
- Cold spots
- Out-of-field dose
- Integral dose

Requirements

- High spatial resolution
- Small dosimetric “voxels“
- Ease of operation, non-toxic
- Reasonable cost
- Fast readout
- Stable in time; reproducible
- Signal proportional to dose (or known functional relation)
- Dose rate independent, large dynamic range
- Orientation independent
- Water-equivalence
- Minimal/managable perturbing

passive (scattered) – dynamic (scanned)

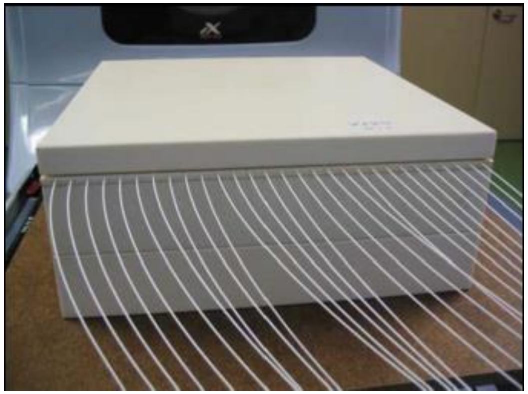


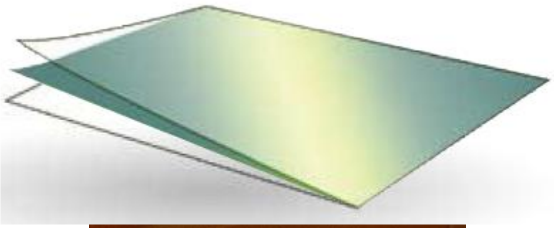
Scanning for passive beams

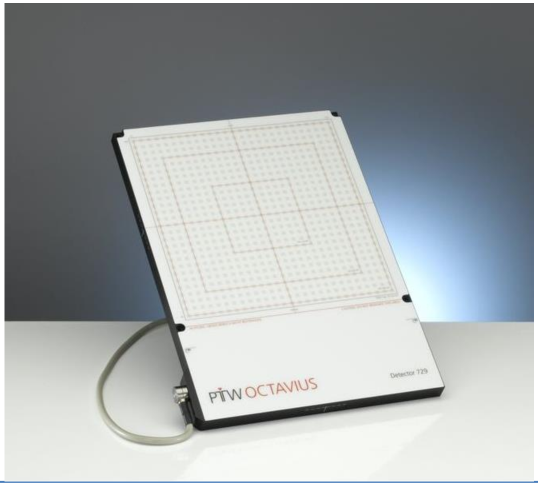
+

Arrays and 2D, 3D dosimeters for dynamic beams

→







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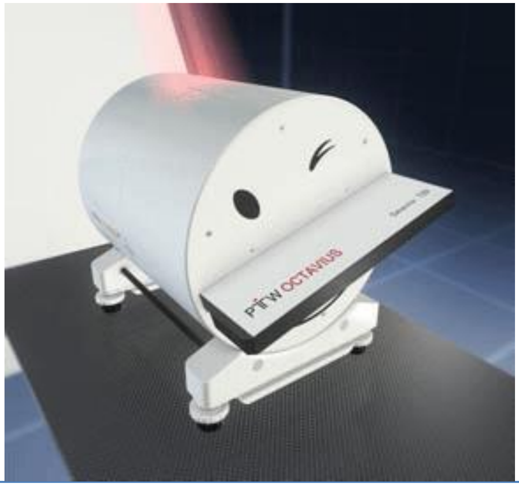
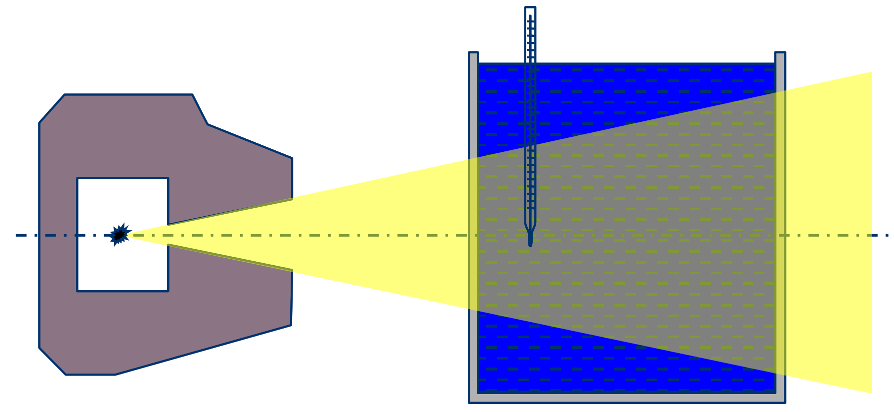


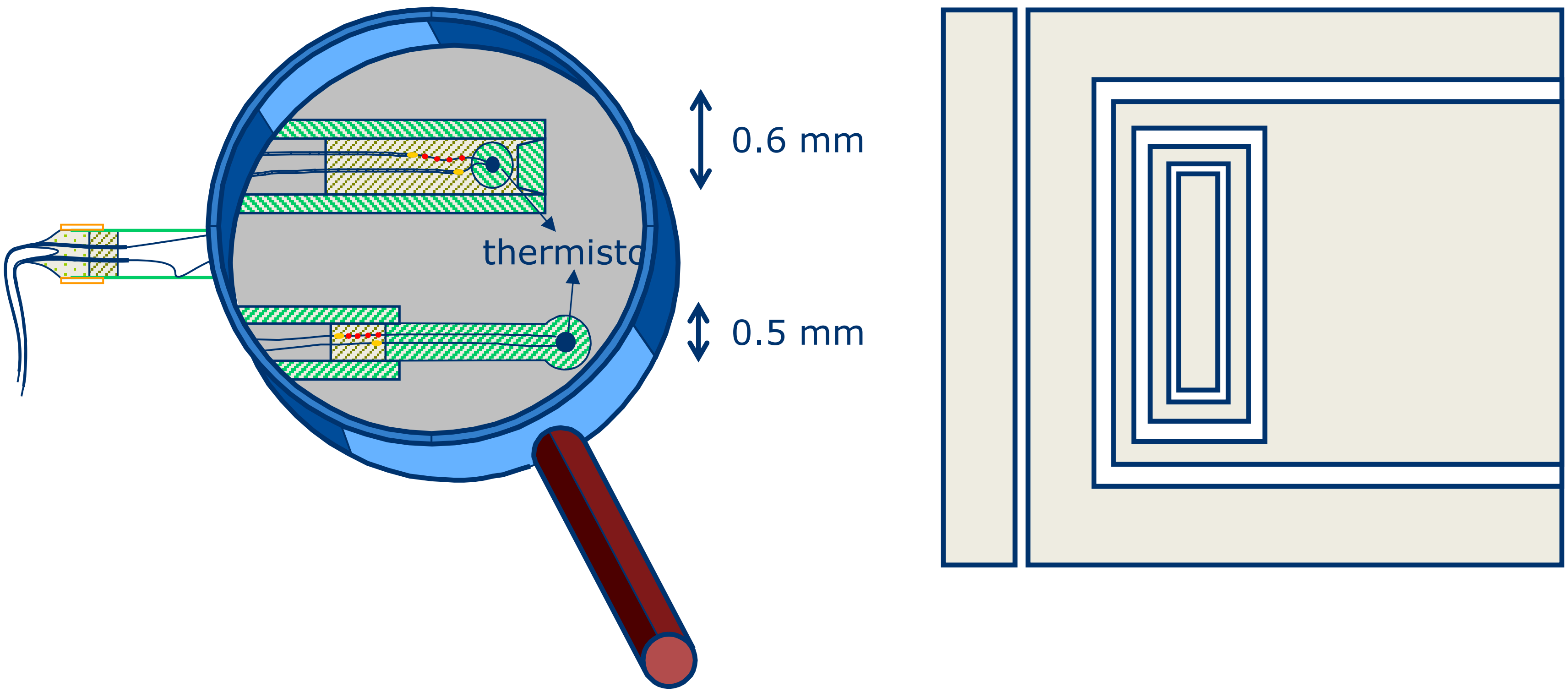
Calorimetry (thermalisation)

$$D_{med} = c_{med} \cdot \Delta T$$

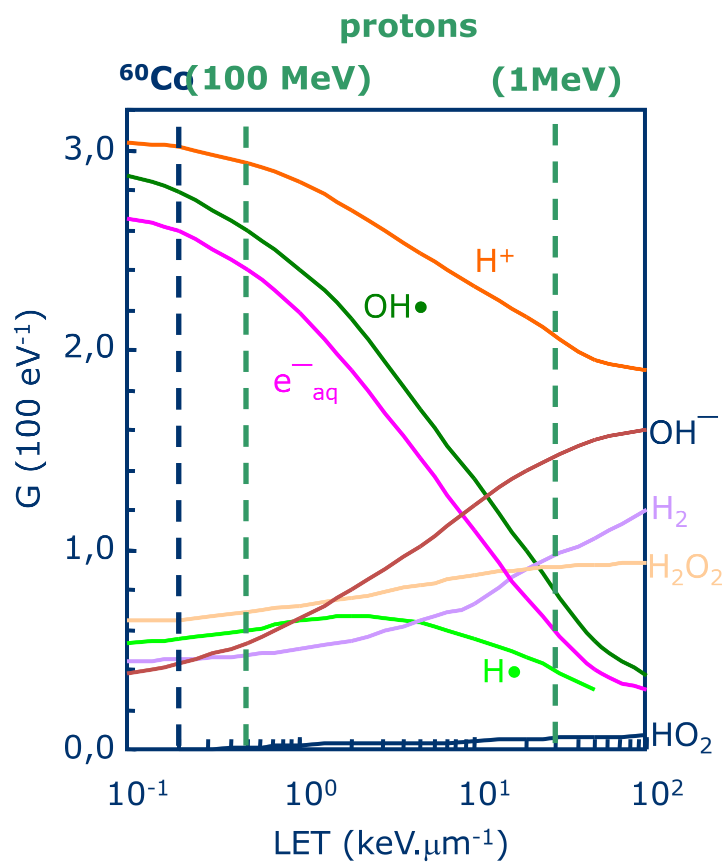


	c (J·kg^{-1}·K^{-1})	$\Delta T/D$ (mK·Gy^{-1})	α (m^2·s^{-1})
water	4180	0.24	1.44×10^{-7}
graphite	710	1.41	0.80×10^{-4}

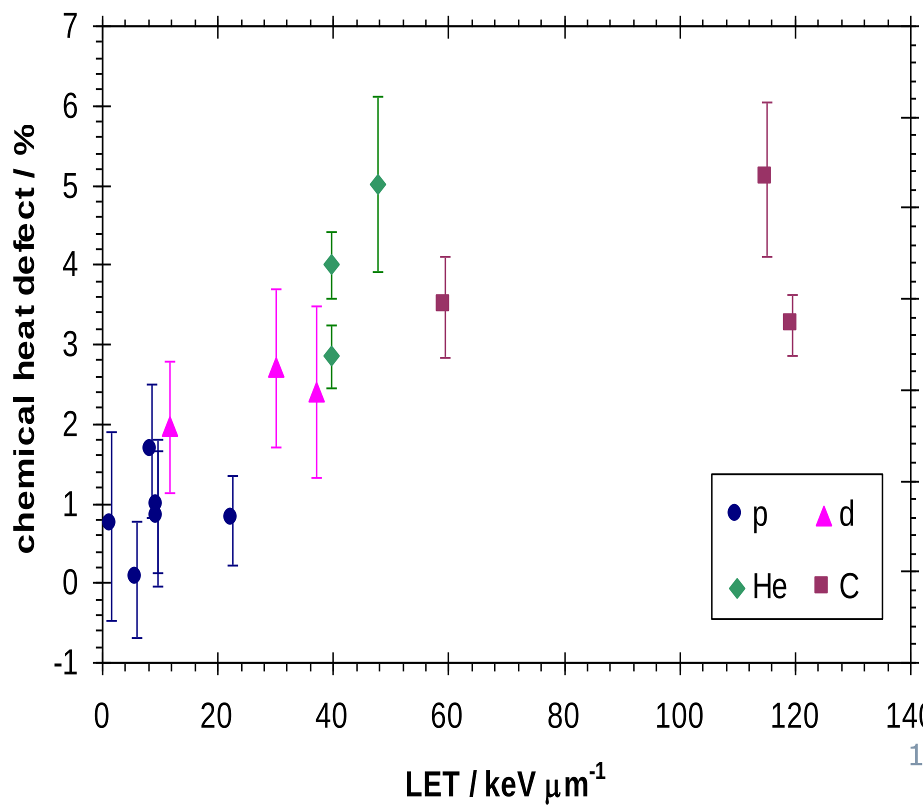
Calorimeters - water vs graphite



Water calorimeters – energy independent chemical heat defect?



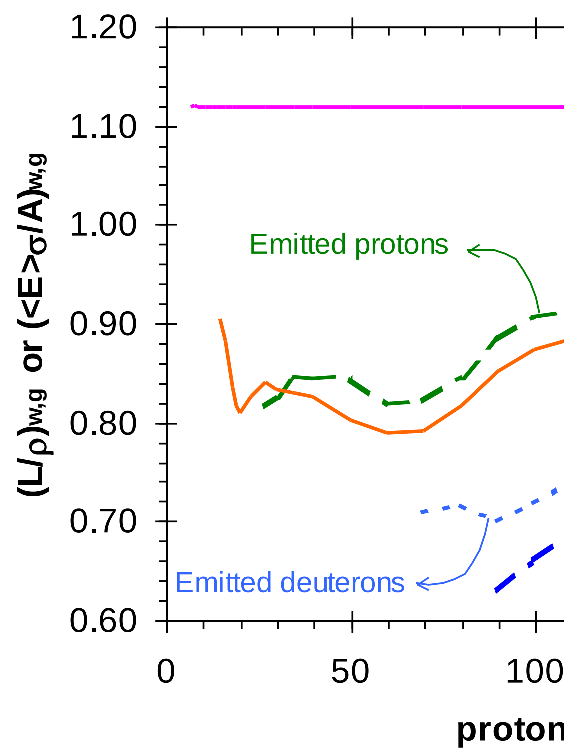
Ross et al (1996) Phys. Med. Biol. 41:1

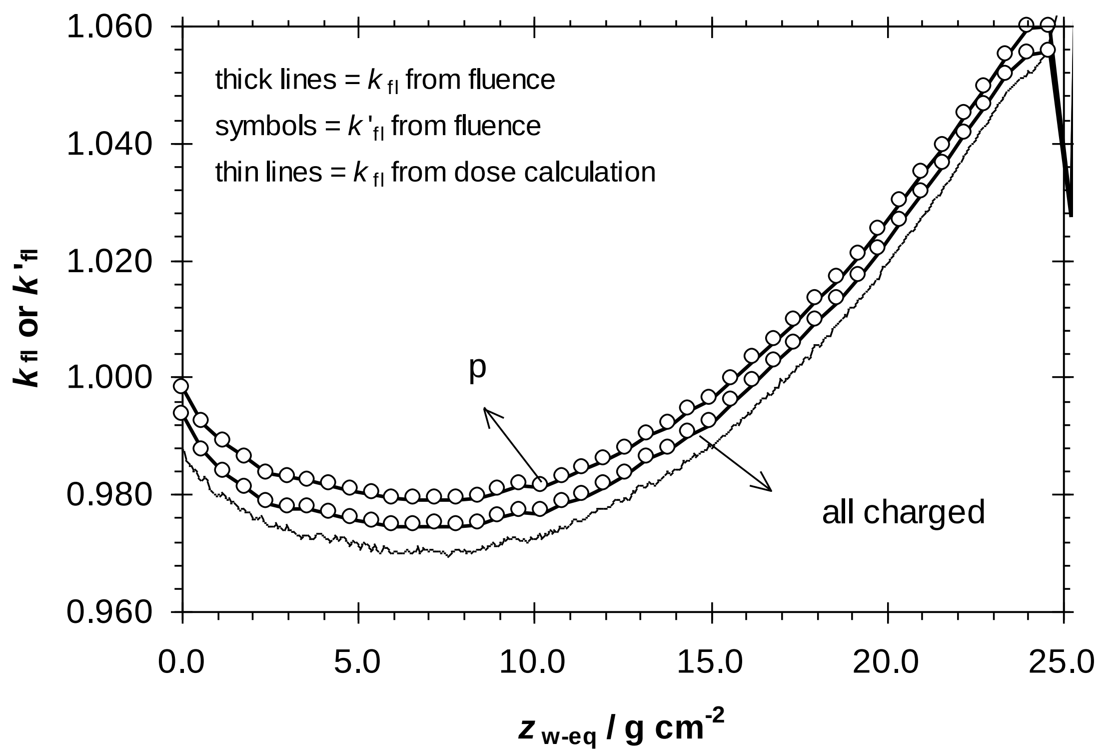


Brede et al (2006) Phys. Med. Biol. 51:3667

Graphite calorimeters – energy independent dose conversion?

$$D_w(z_w) = D_g(z_g) \cdot \left(\frac{S}{\rho}\right)_g^w \quad ?$$





Acta Oncologica, 2011; 50: 797–805

informa healthcare

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Phys. Med. Biol. 58 (2013)

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Conversion f
an 80 MeV/A

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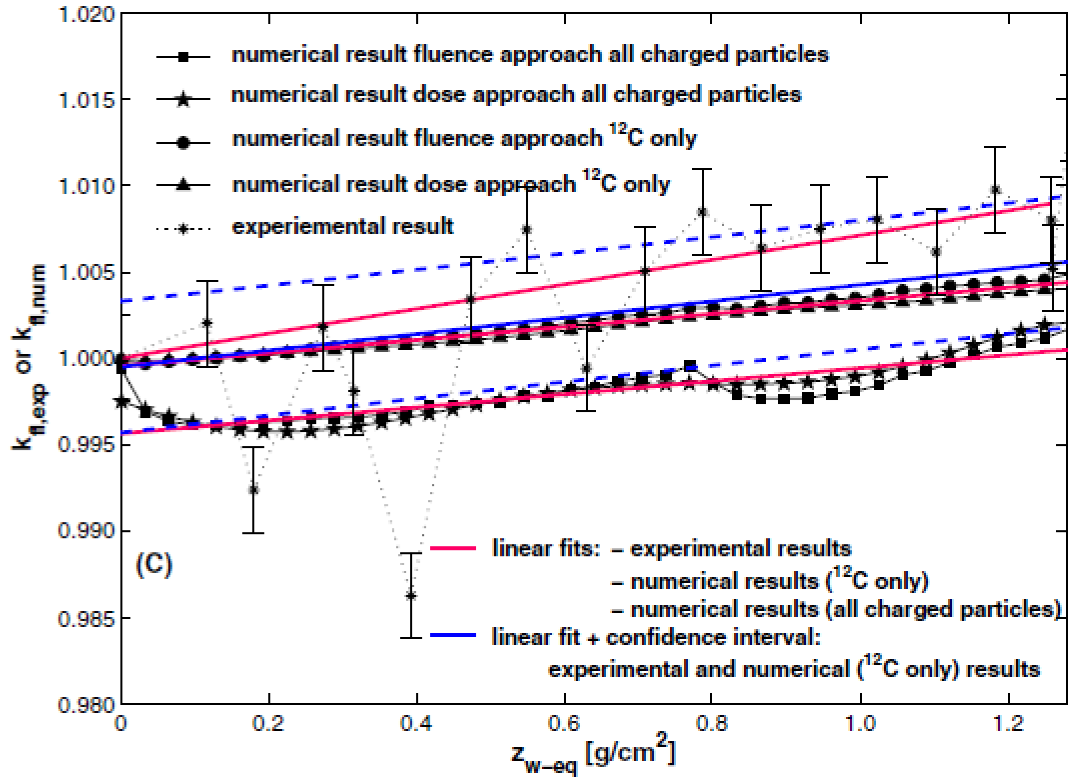
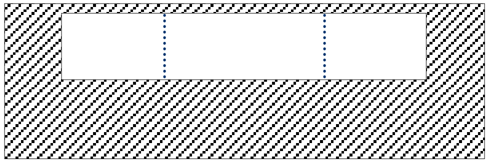


Figure 6. Numerical and experimental fluence correction factors for an 80 MeV/A carbon ion beam as a function of water-equivalent depth. (A) and (B) show the experimental data only and (C) shows a comparison of numerical and experimental results up to the Bragg peak region. In (C), solid circles and solid squares are based on the fluence approach of equation (2.7*a*), and solid triangles are based on the dose approach of equation (2.8*a*). The solid circles and solid triangles show results where only the carbon ion spectrum has been considered, while for the solid squares and the solid stars, all the charged particles spectra have been included.

Ionization chambers



Dose determination with ion chamber

$$D_w = D_{air}\, s_{w,air}\, p$$

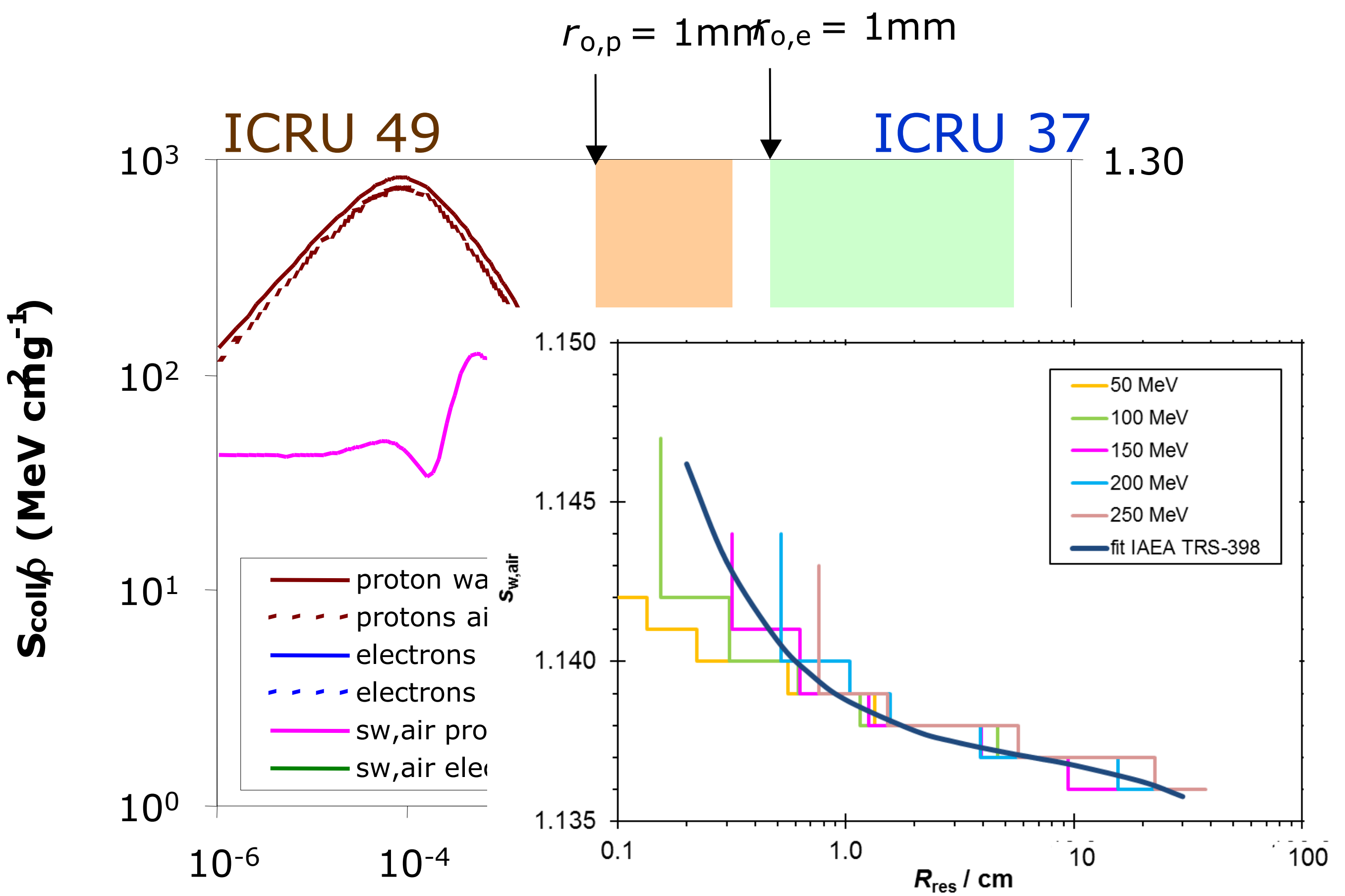
$$D_{air} = \frac{Q}{m_{air}} \frac{W}{e} = \frac{Q}{\rho\, V_{air}} \frac{W}{e}$$

Q: charge produced in the air of the chamber
W: mean energy required to produce an ion-pair in air

Unfortunately, for commercially available chambers, the volume *V* is not known with the necessary accuracy (would otherwise be a primary standard!).

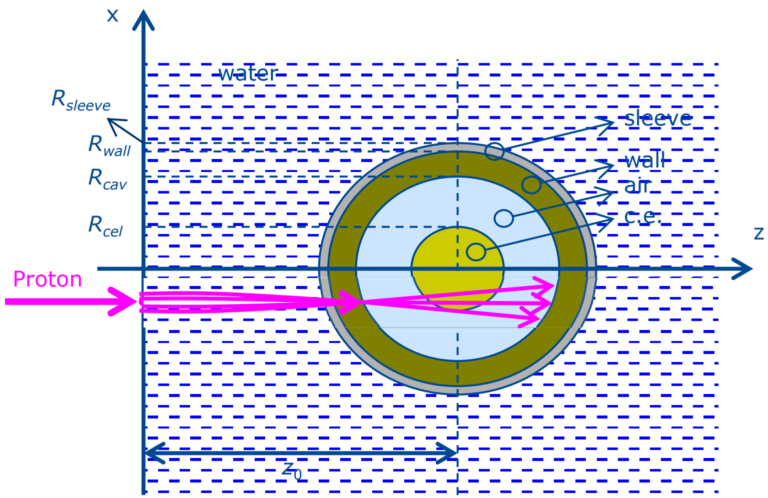
We have to rely on methods other than "first principles", which involve the use of ion chamber calibration factors

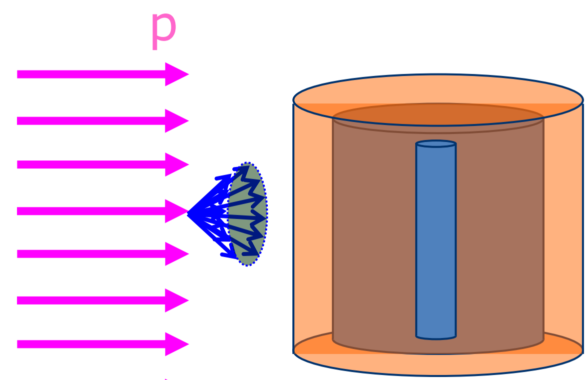
Water/air stopping power ratio

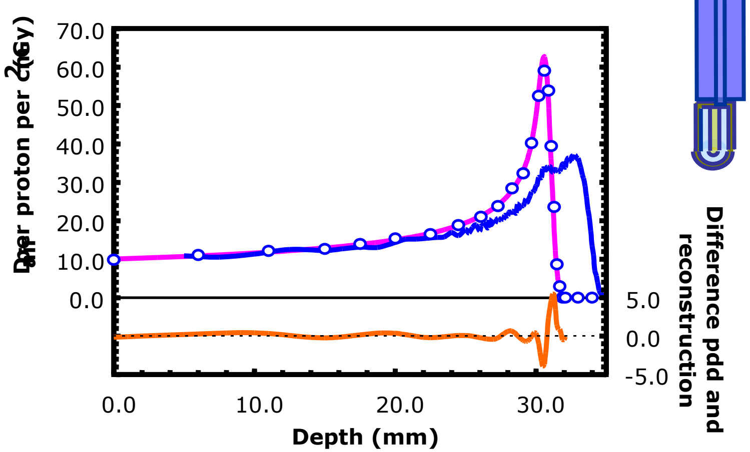


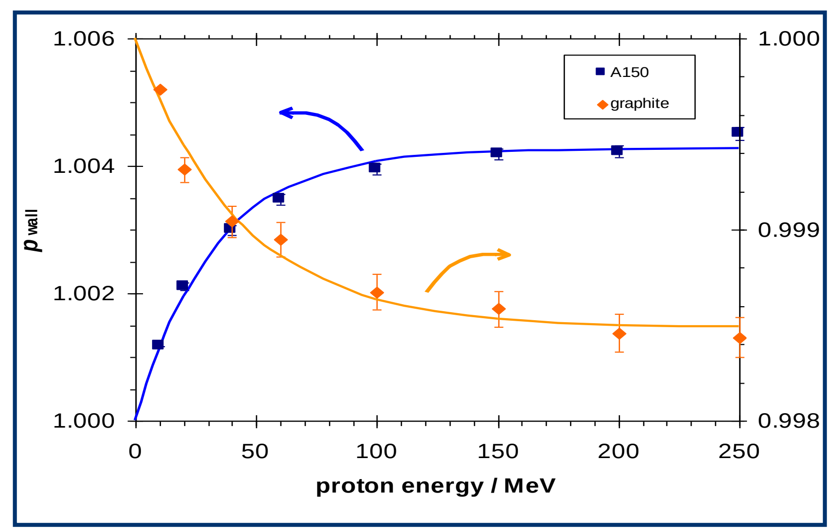
Medin et al. 1997, Phys Med Biol 42:89

Perturbation correction factors





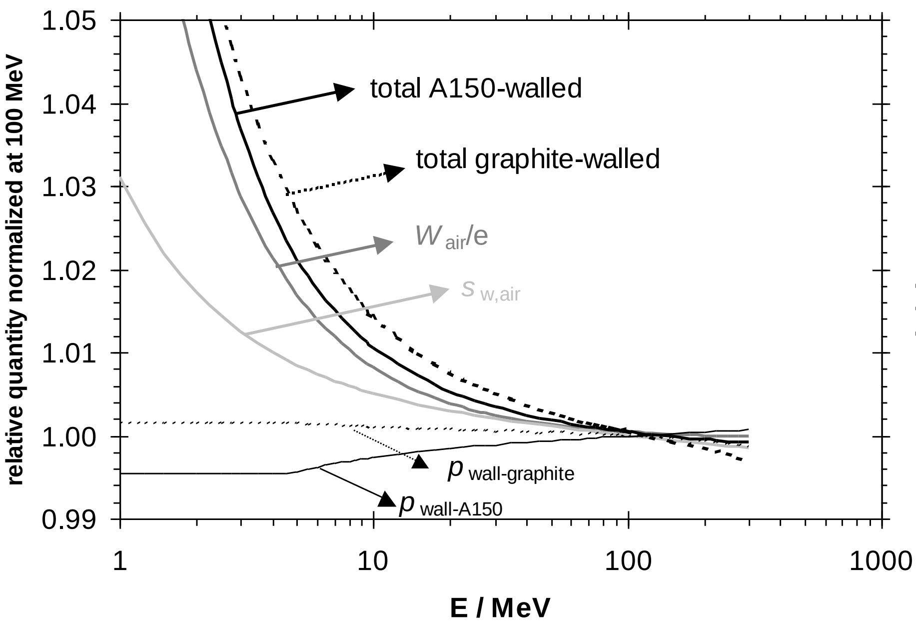


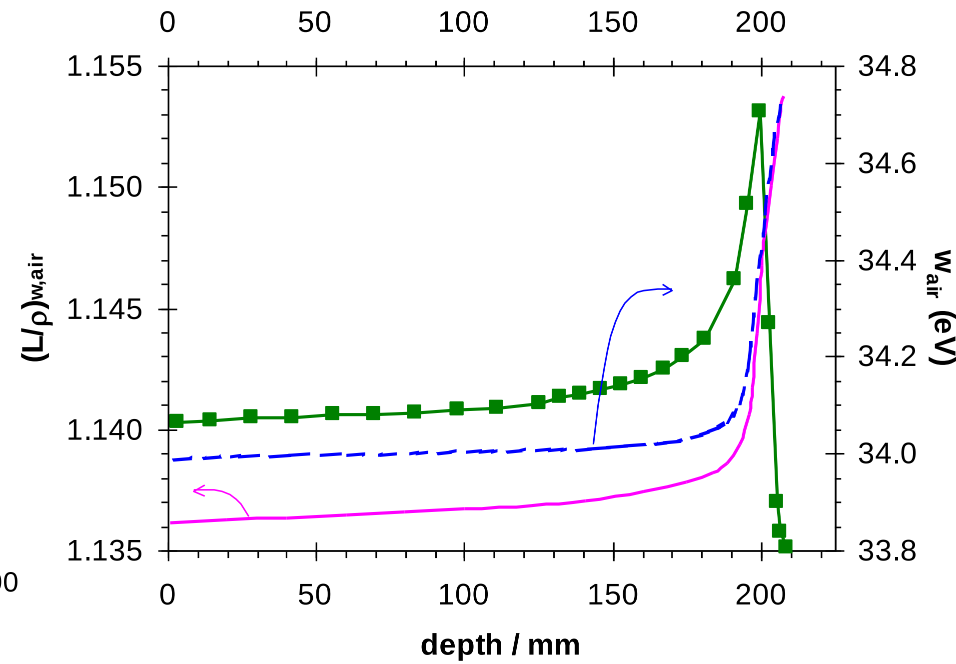


Palmans 2006 Phys Med Biol 51:3483

Palmans 2011 Proc IDOS IAEA-CN182-230

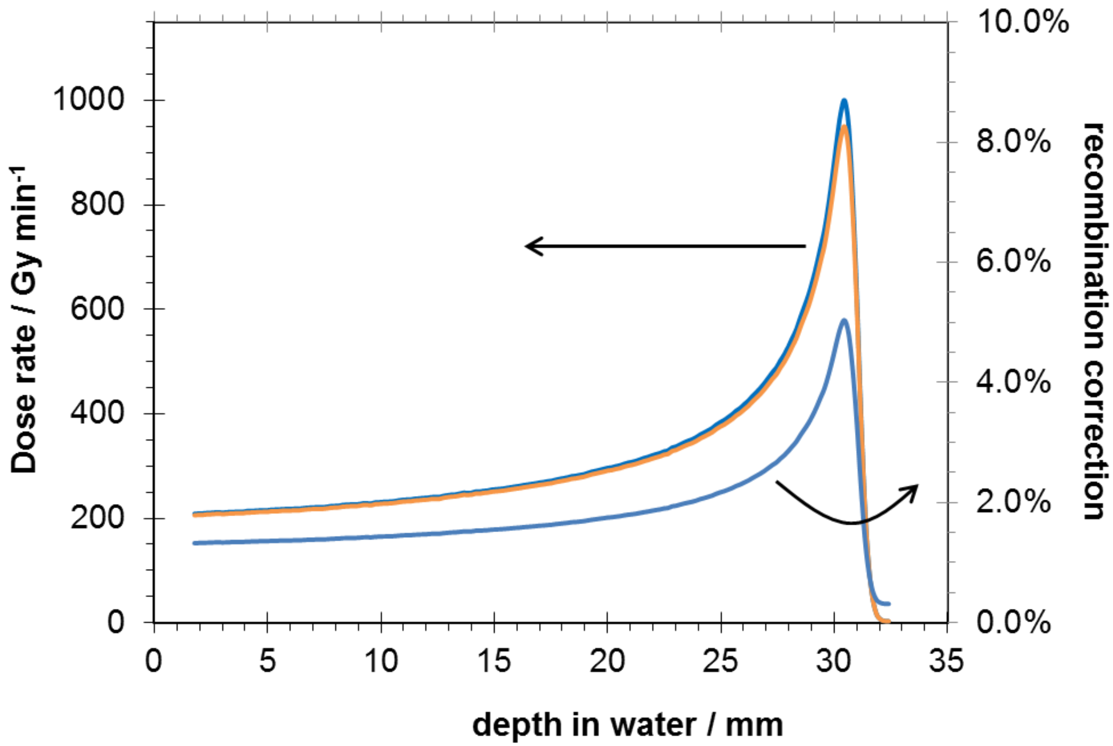
Ionisation chambers – overall conversion air to dose





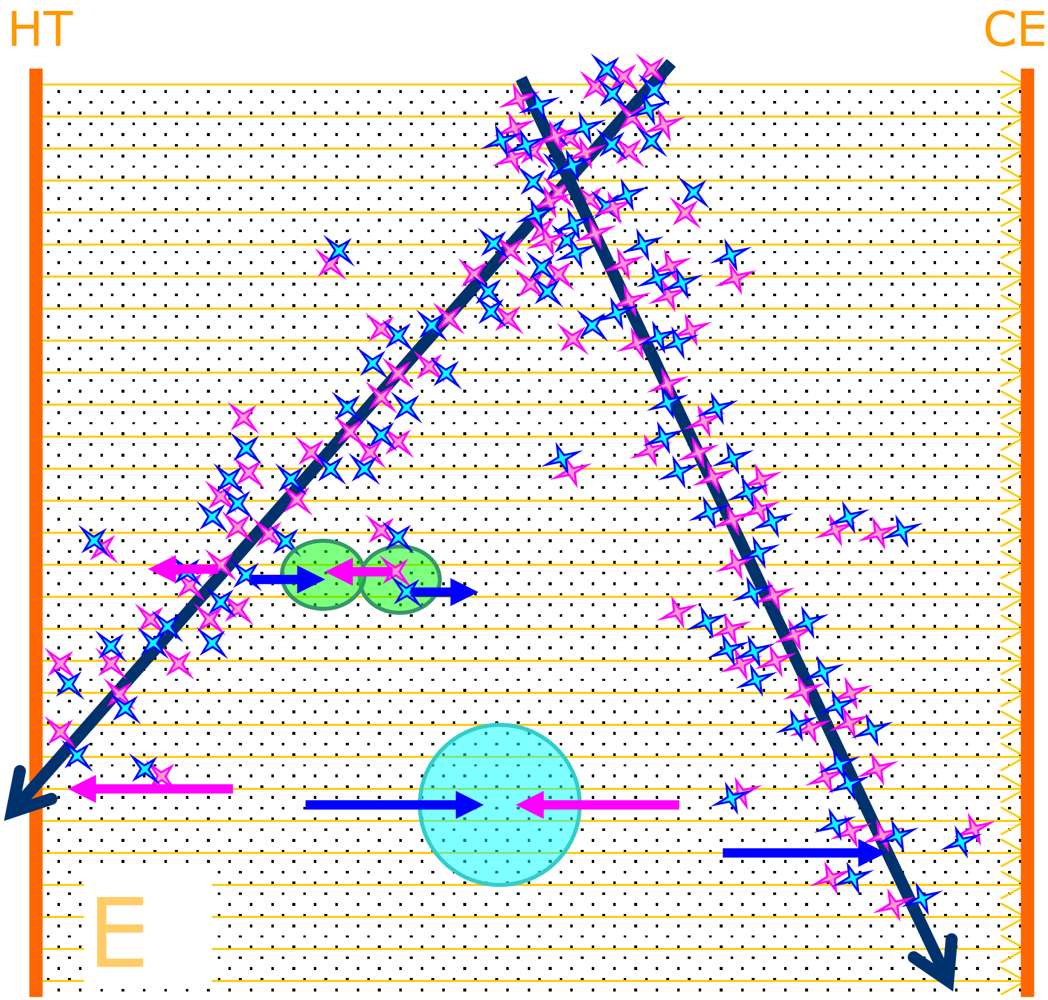
Palmans, Dosimetry, in : Proton Therapy Physics, Ed Paganetti

Ionisation chambers (& any ionisation detector) – charge recombination



Palmans et al 2006 NPL report DQL-RD003

Ion chambers - recombination



- Initial recombination

$$\sim \frac{1}{E}$$

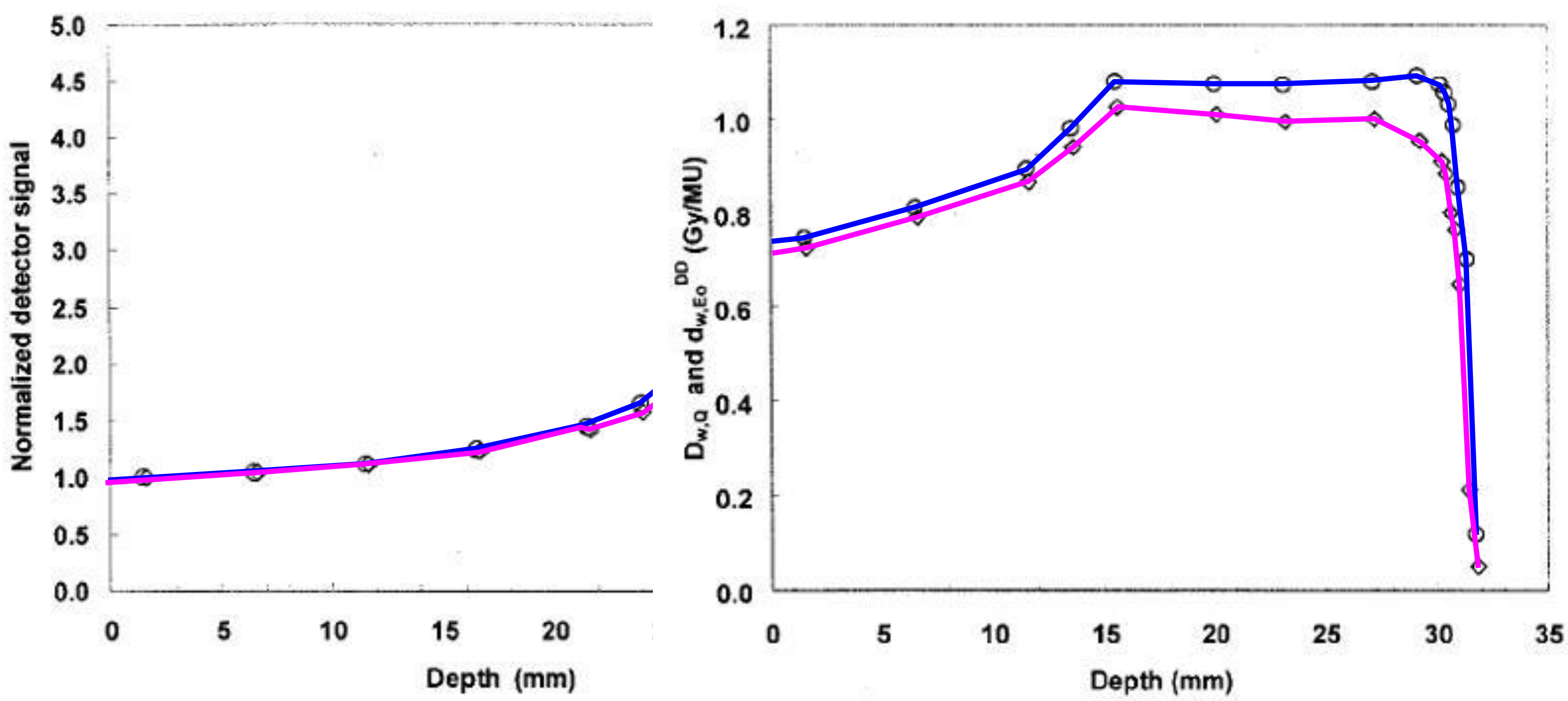
- Volume recombination

$$\sim \frac{q}{E} \qquad \sim \frac{i}{E^2}$$

(pulsed) (continuous)

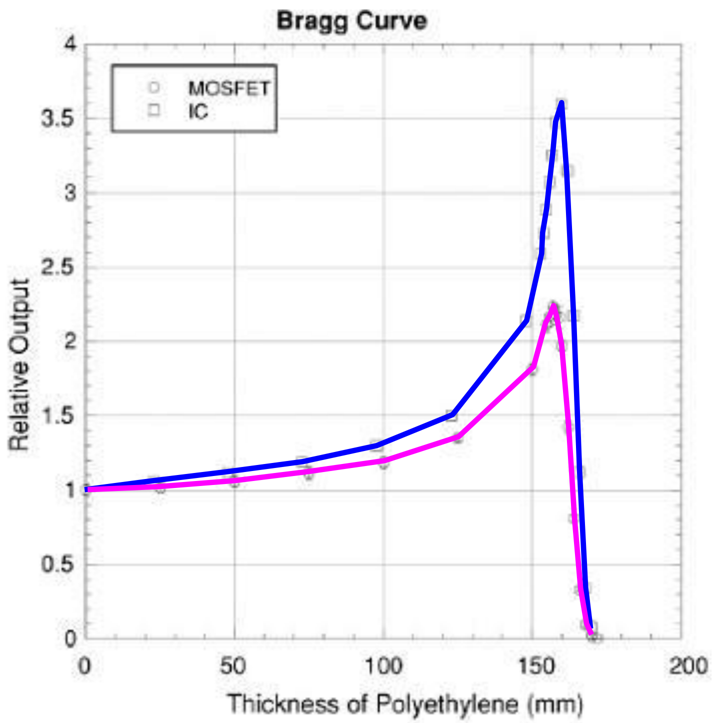
- Charge multiplication

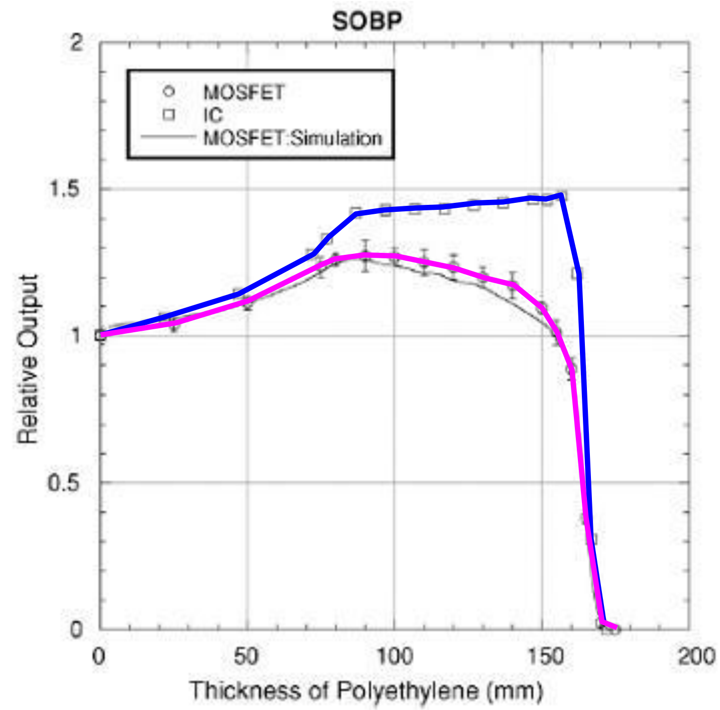
diamond detectors



Fidanzio et al 2002 Med Phys 29:669

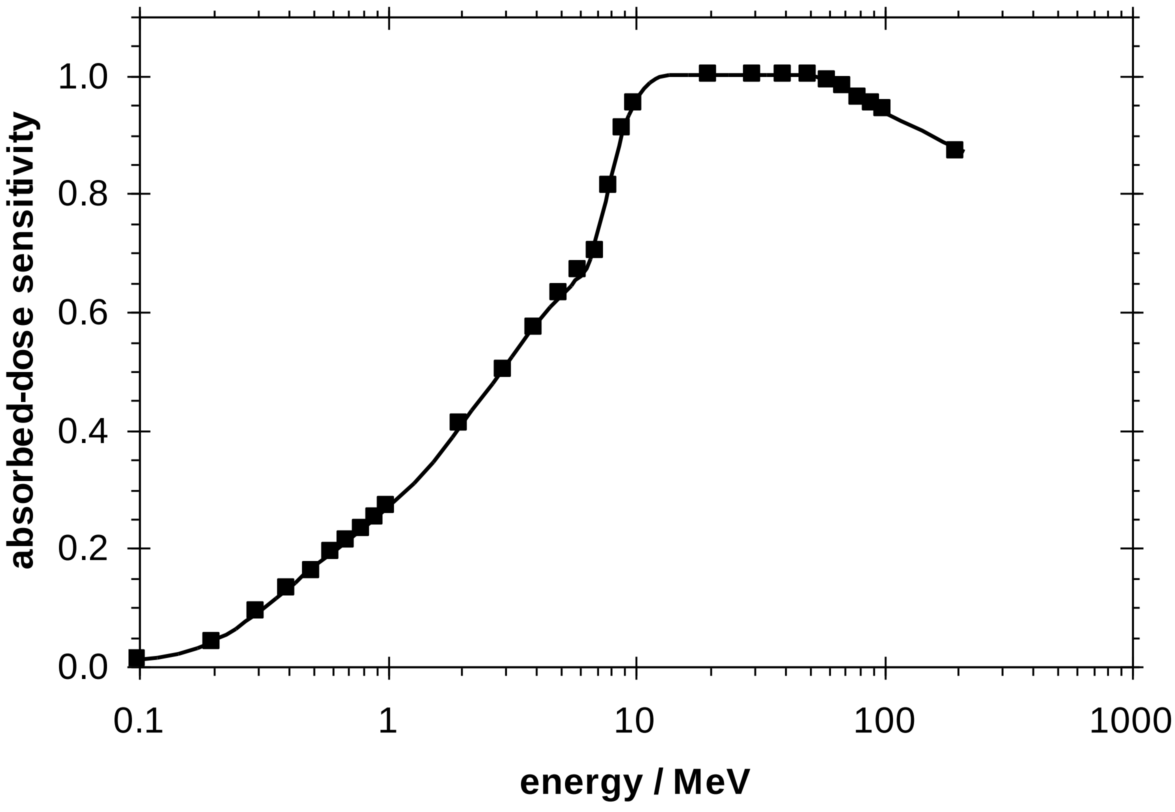
Silicon-based detectors





Kohno et al 2006 Phys Med Biol 51:6077

TLD - protons



Besserer et al 2001 Phys Med Biol 46:473

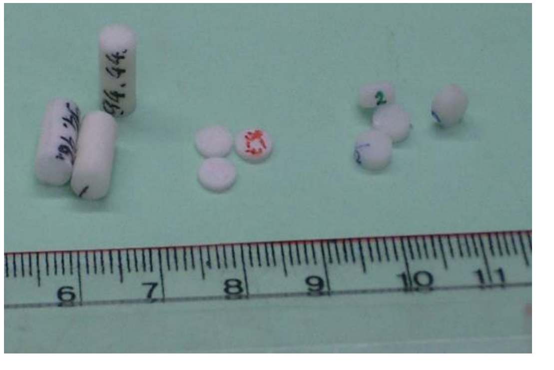
NPL therapy level alanine/EPR

Operates since 1991

Bruker ESP 300 X-band 9" magnet

Pellets

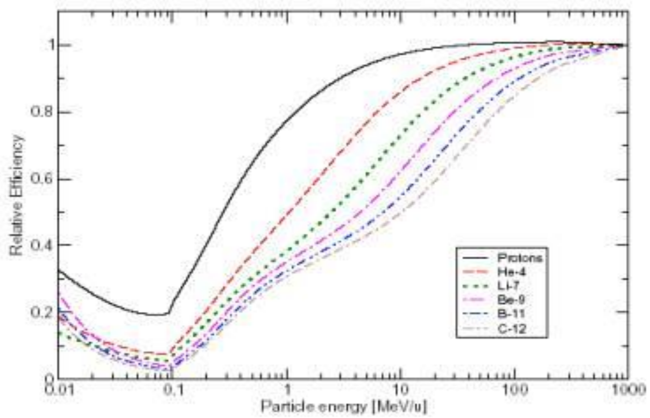
- 90% alanine + 10% paraffin wax
- 5 mm diameter
- 0.5 mm and 2.5 mm nominal thickness



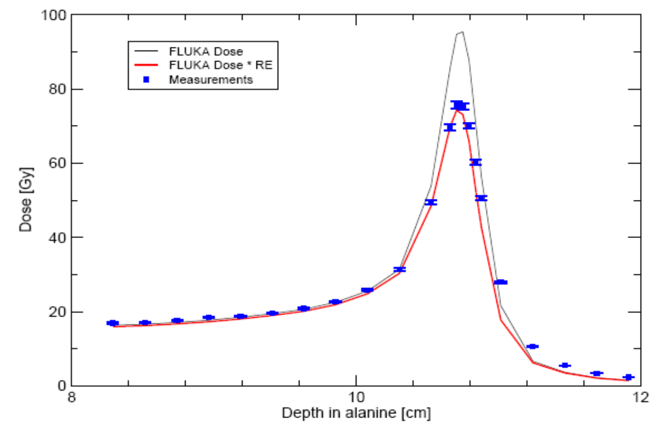
Measurement reproducibility of
2.5 mm pellets ~ 0.05 Gy

Alanine/EPR dosimetry

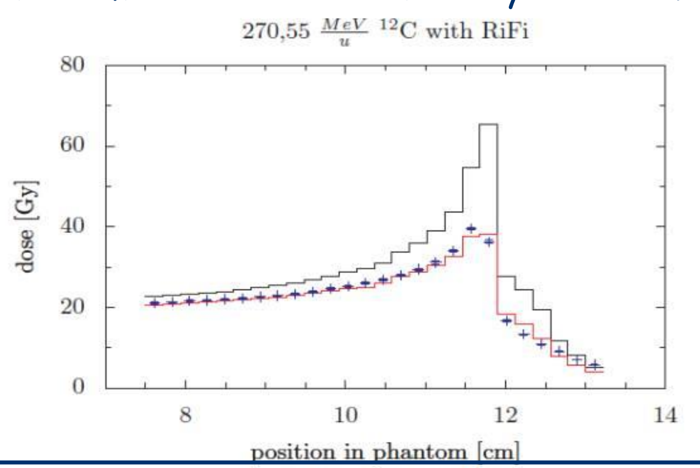
Bassler et al, NIMB 266 929-936, 2008



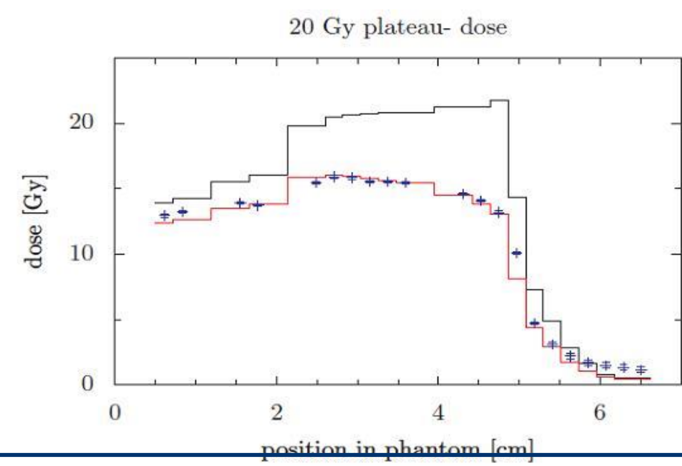
CERN anti-proton beam



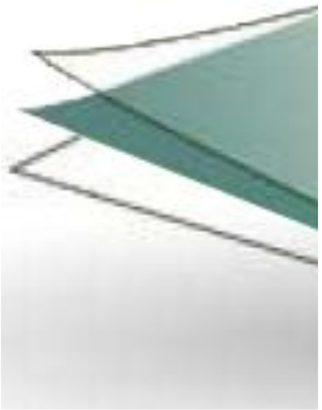
Herrmann et al 2011 Med Phys 38:1859

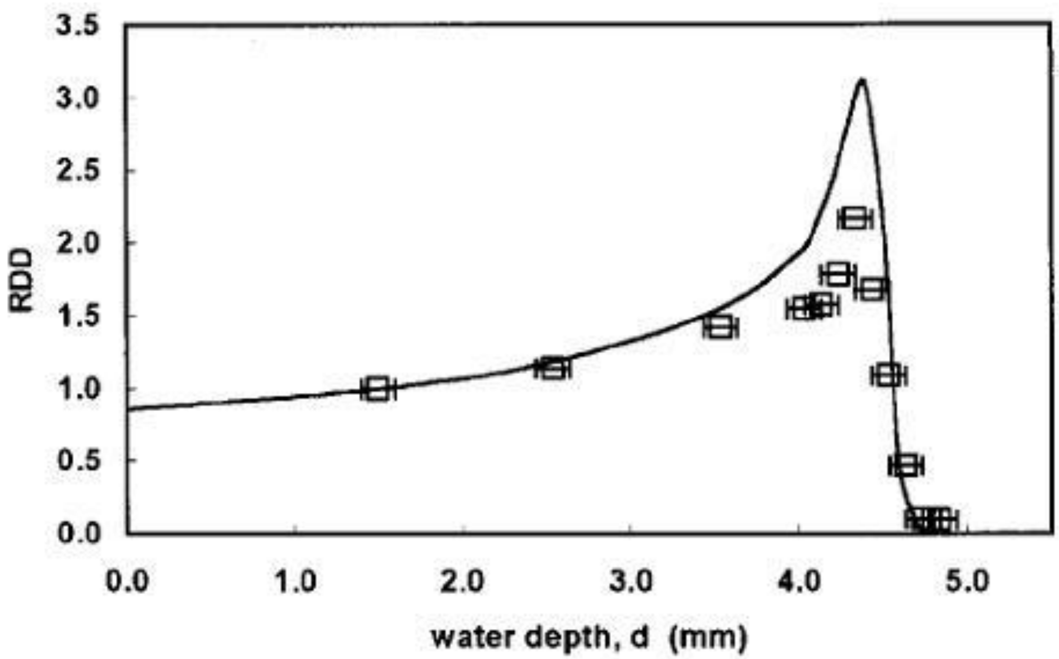


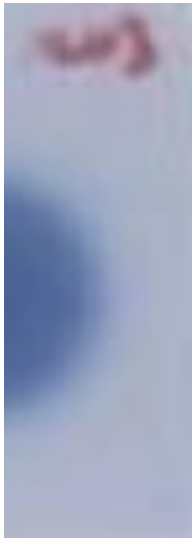
GSI ^{12}C ion beam



Radiochromic film

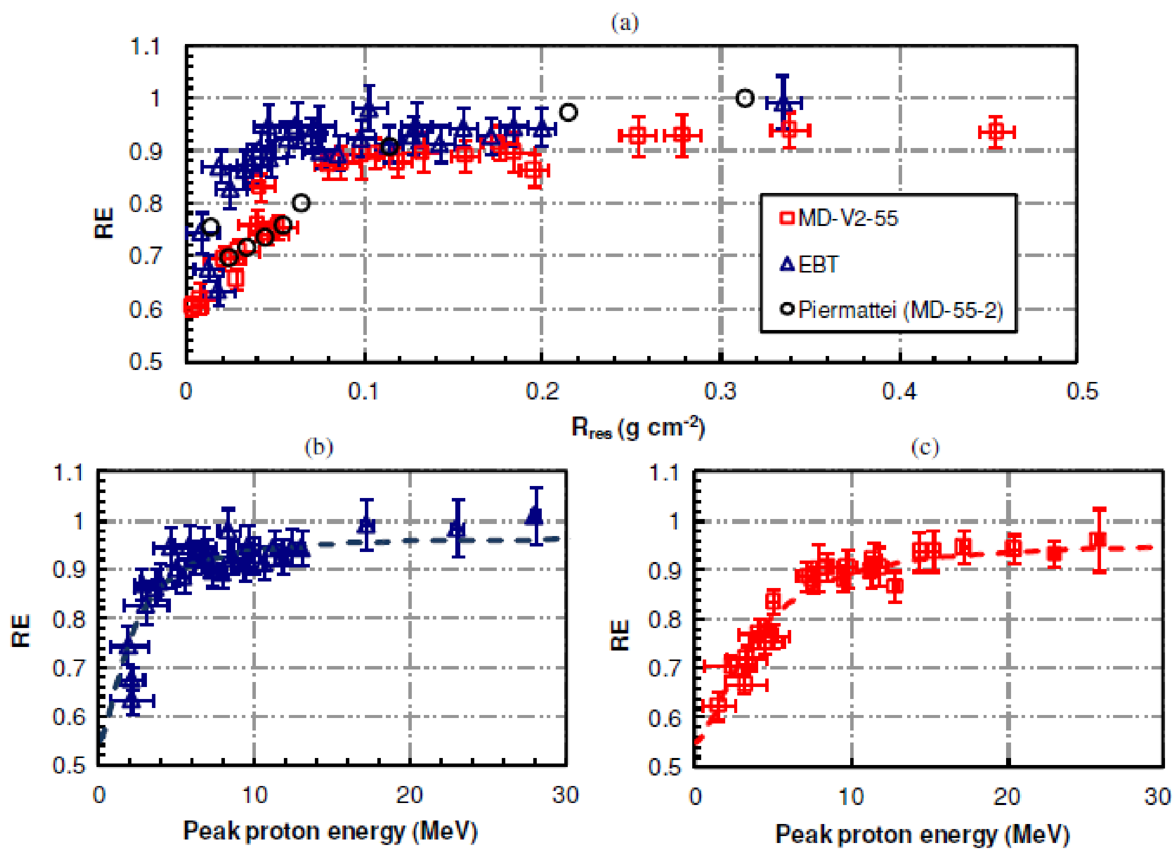






Piermattei et al 2000 Med Phys 27:1655

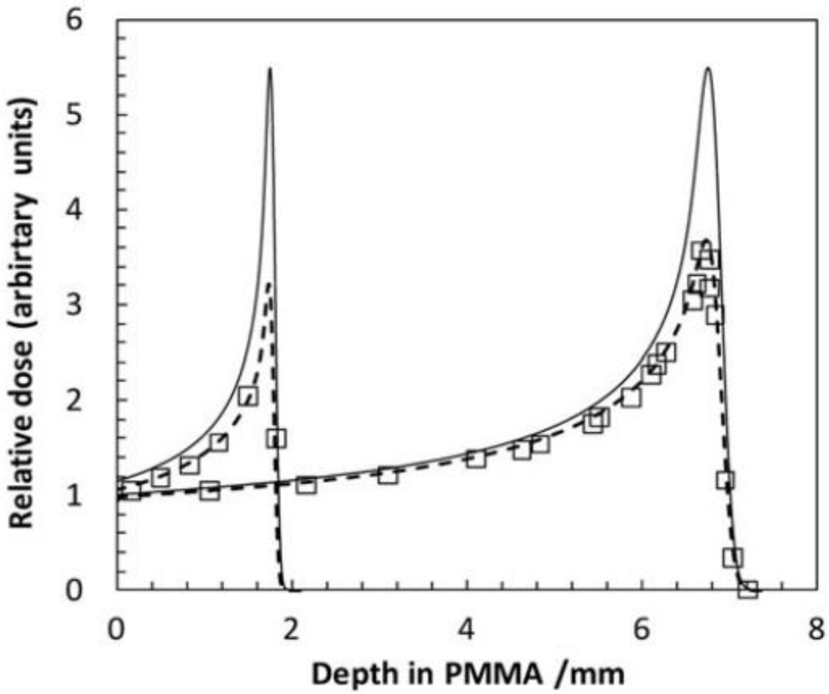
Radiochromic film – energy dependence



Kirby et al. 2010 Phys Med Biol 55:417

An interesting one… depth dose distribution for fluence determination

Pic laser induced beam



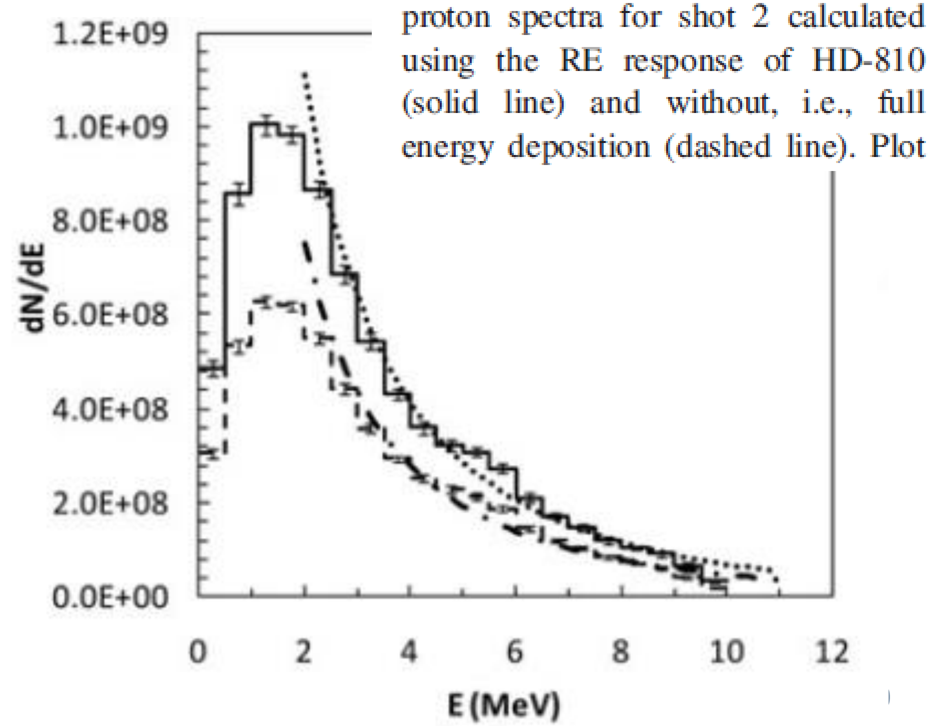


Fig. 9. Plot (a) shows a comparison of proton spectra for shot 2 calculated using the RE response of HD-810 (solid line) and without, i.e., full energy deposition (dashed line). Plot

Kirby et al. 2011 Laser Part Beams 29:231

Alanine – plan verification

Radiotherapy and Oncology 108 (2013) 99–106

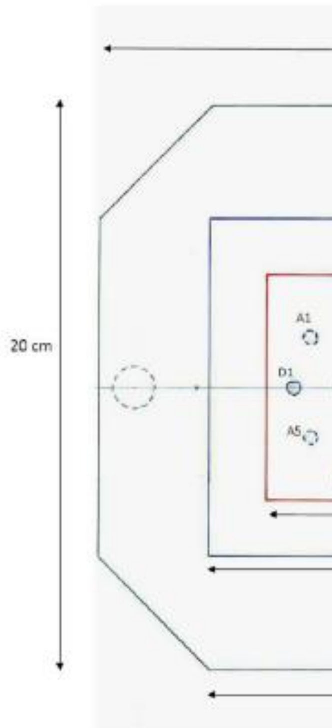


Table 2
Results of dose measurements in a carbon ion beam with 20 alanine dosimeters and with a Farmer chamber. The different conversion factors for each alanine pellet (A1–D5) and their overall mean dose are listed explicitly.

Dosimeter	TPS	TPS corrected for daily output	$D_{w,^{60}Co}$ [Gy]	Relative effectiveness	$(\mu_{en}^{^{60}Co}/\rho)_w^{al}$	$(S^{^{12}C}/\rho)_{al}^w$	$D_{w,^{12}C}$ (Gy)	Deviation (%)
A1	10.01	9.89	7.42	0.747	0.970	1.016	9.80	−0.9
A2	10.05	9.93	7.41	0.748	0.970	1.016	9.76	−1.6
A3	10.05	9.93	7.30	0.744	0.970	1.016	9.67	−2.6
A4	10.00	9.88	7.35	0.745	0.970	1.016	9.73	−1.4
A5	9.94	9.82	7.36	0.748	0.970	1.016	9.69	−1.2
B1	10.01	9.89	8.27	0.840	0.970	1.017	9.73	−1.6
B2	10.02	9.90	8.22	0.839	0.970	1.017	9.67	−2.3
B3	10.01	9.89	8.23	0.840	0.970	1.017	9.67	−2.2
B4	10.00	9.88	8.24	0.840	0.970	1.017	9.68	−2.0
B5	9.97	9.85	8.28	0.839	0.970	1.017	9.73	−1.1
C1	10.05	9.93	8.55	0.876	0.970	1.018	9.63	−3.0
C2	10.04	9.92	8.56	0.877	0.970	1.018	9.64	−2.8
C3	10.03	9.91	8.40	0.877	0.970	1.018	9.46	−4.5
C4	10.04	9.92	8.62	0.878	0.970	1.018	9.69	−2.2
C5	10.06	9.93	8.60	0.877	0.970	1.018	9.68	−2.5
D1	10.02	9.90	8.59	0.900	0.970	1.018	9.43	−4.7
D2	10.02	9.90	8.86	0.900	0.970	1.018	9.72	−1.7
D3	10.01	9.89	9.00	0.898	0.970	1.018	9.90	0.1
D4	9.99	9.87	8.79	0.897	0.970	1.018	9.67	−1.9
D5	10.05	9.93	8.76	0.898	0.970	1.018	9.63	−2.9
Mean dose	10.02	9.89	–	–	–	–	9.68	**−2.2**
Std. dev.	0.03	0.03	–	–	–	–	0.10	1.1
Farmer chamber	10.00	9.88	–	–	–	–	9.78	**−1.0**

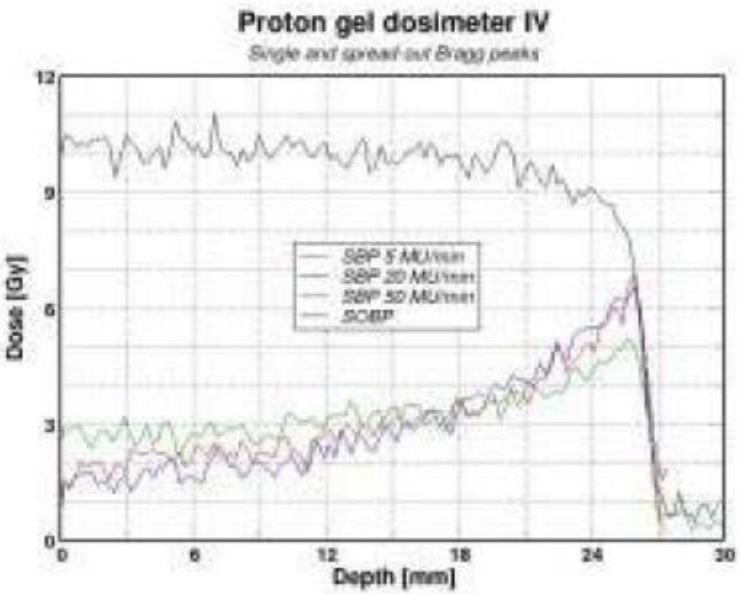
Fig. 1. Drawings of the phantom desi
(b) show the beam direction. A Farm
detectors).

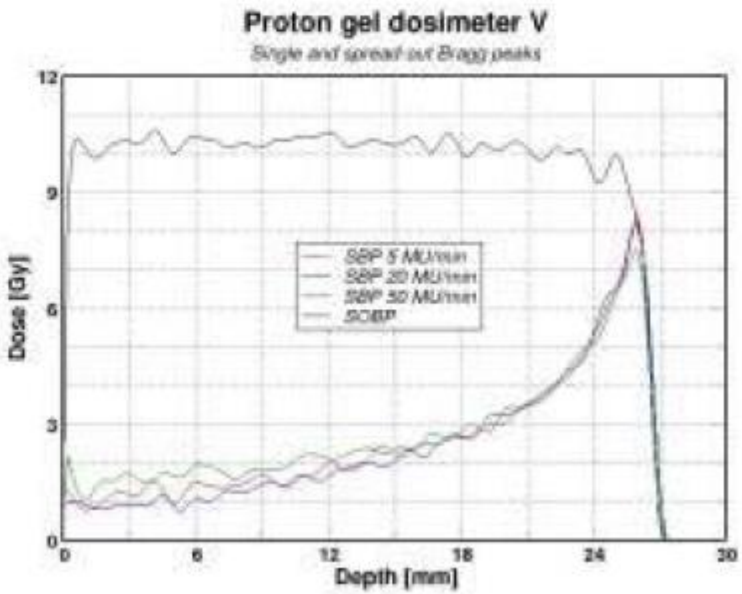
Accepted 27 April 2013
Available online 22 July 2013

of radiation delivery. An end-to-end procedure was designed and tested in both scanned proton and car-

Polymer gels

Polymer gel dosimetry

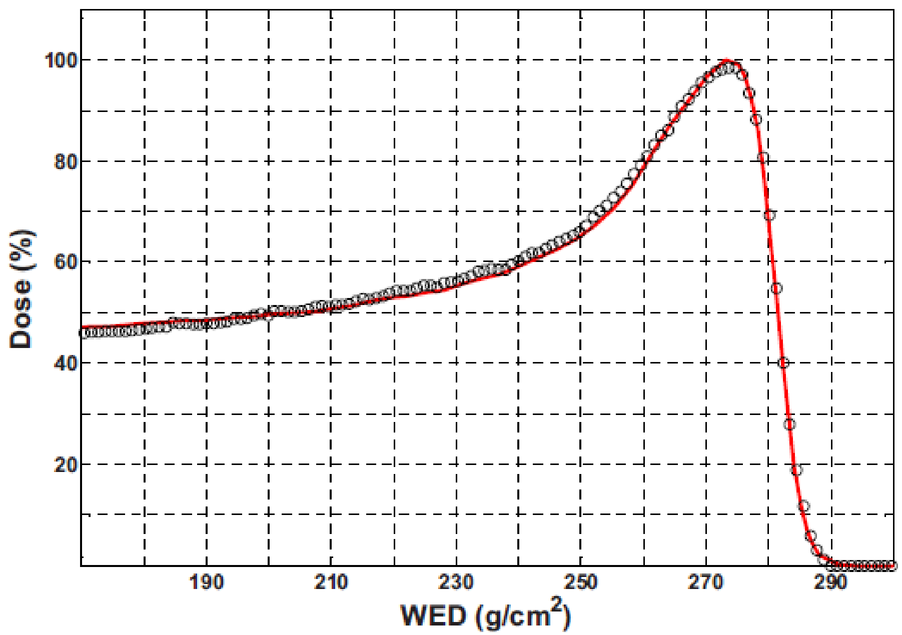


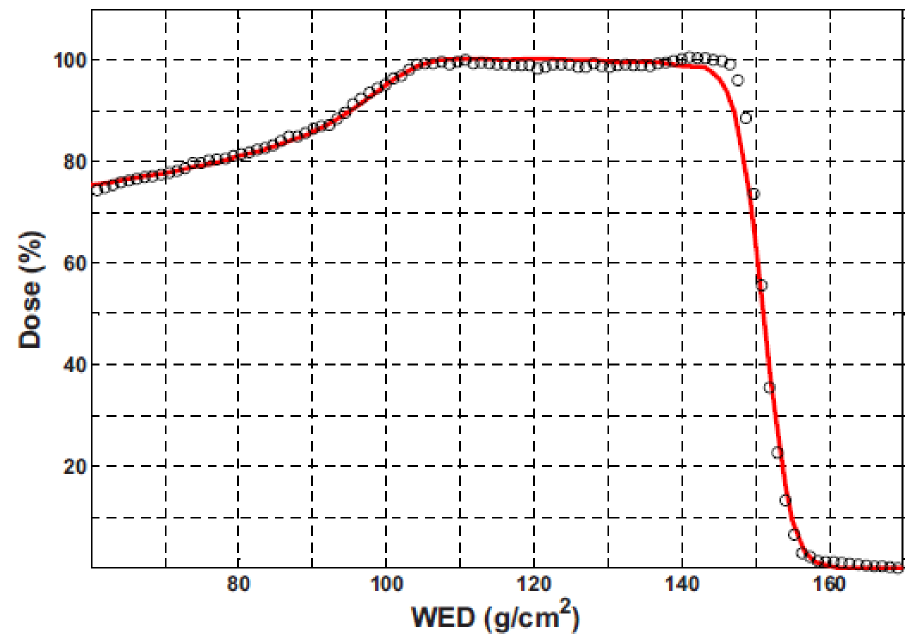


Palmans et al 2006 NPL report DQL-RD003

Polymer gel dosimetry

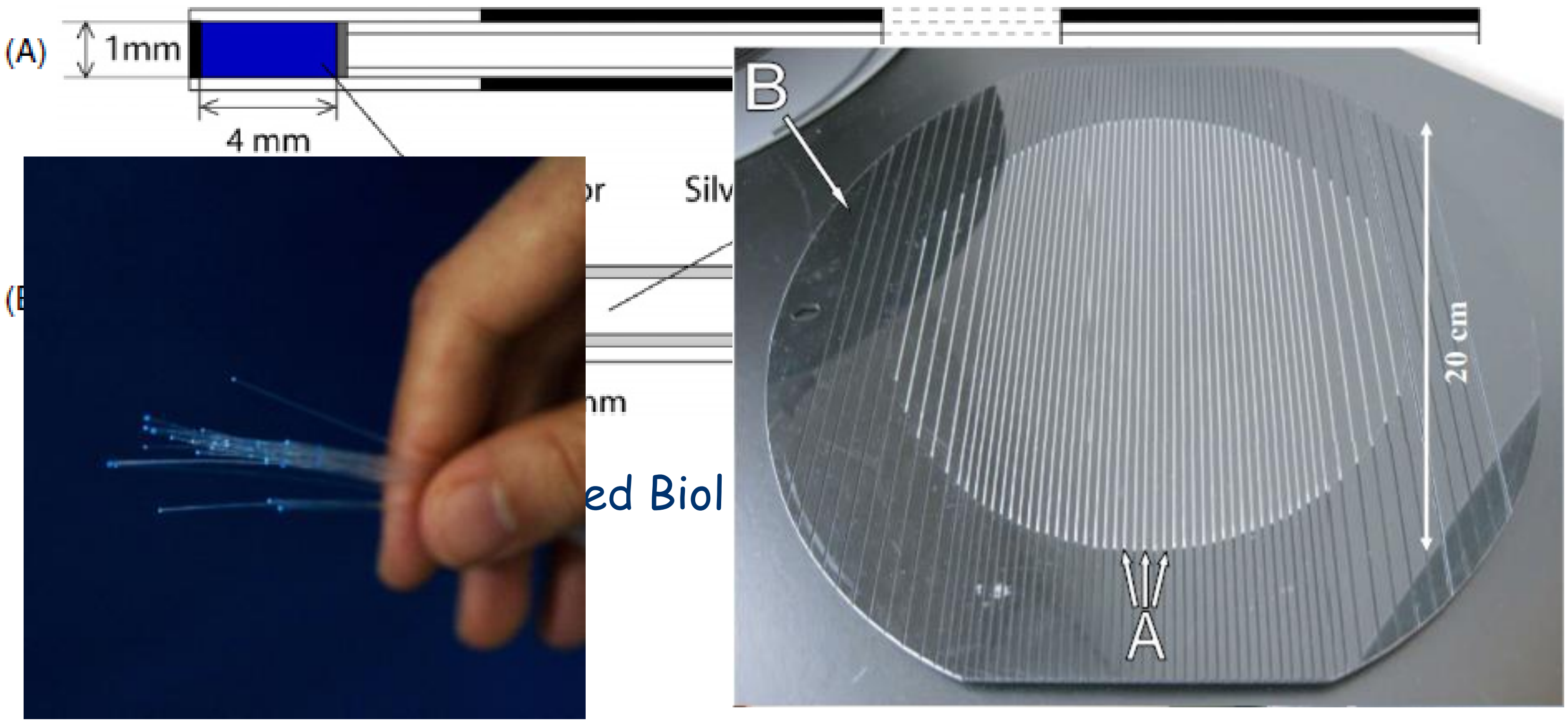
BANG3-Pro2:





Zeidan et al. 2010 Med Phys 37:2145

Plastic scintillators

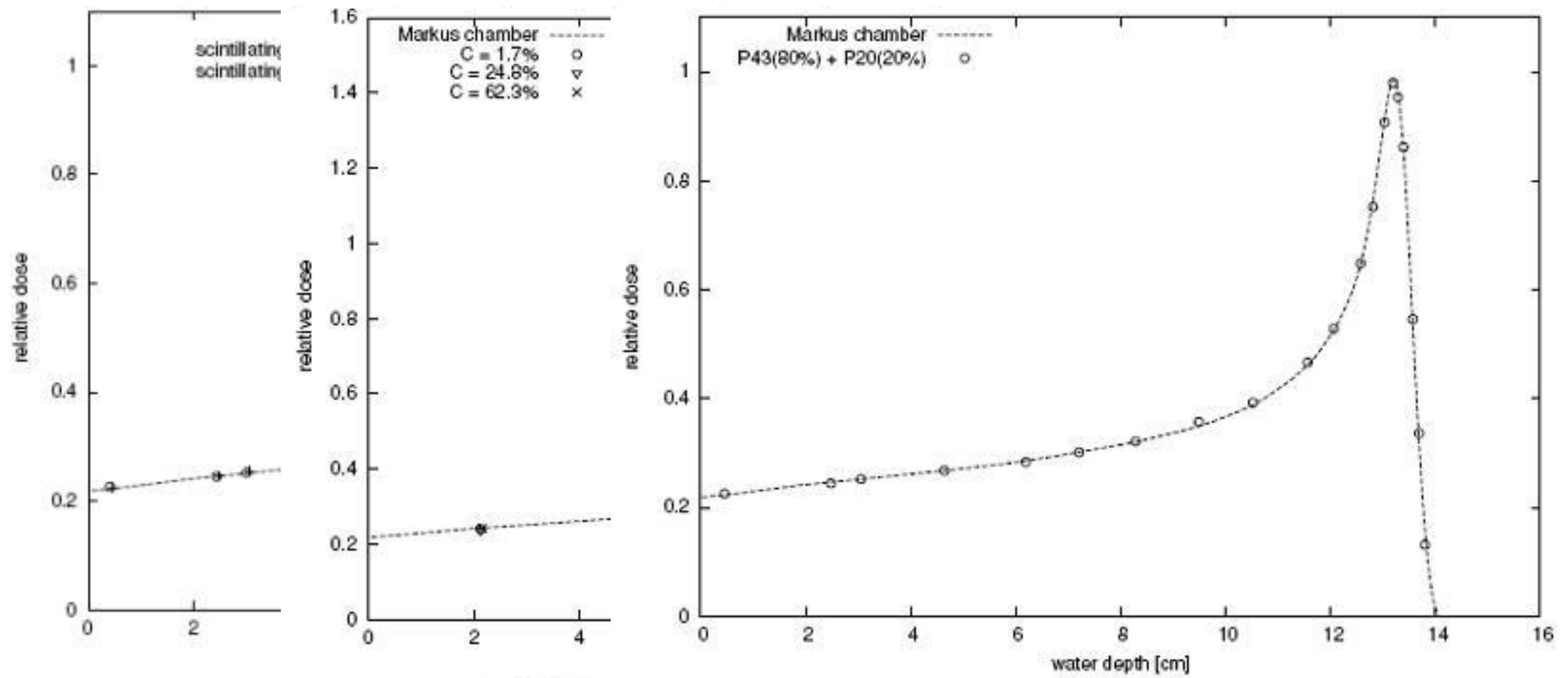


ed Biol

A. Beierholm, Risoe

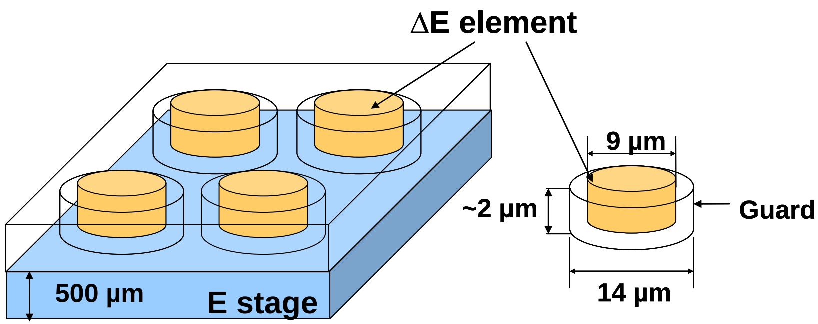
Goulet et al. 2012 Med Phys 39:4840

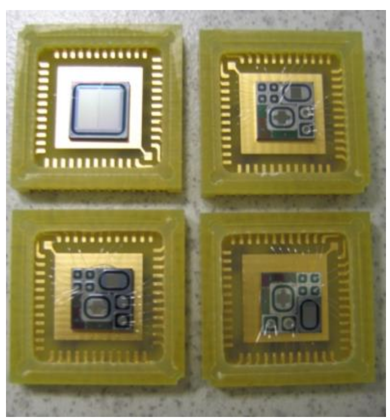
Scintillators



Safai et al. 2004 Phys. Med. Biol. 49:4637

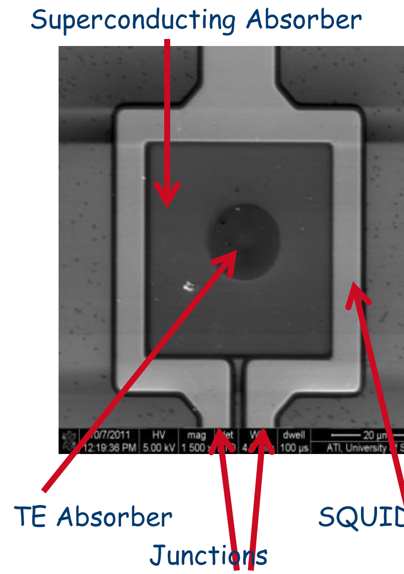
Microdosimetry…

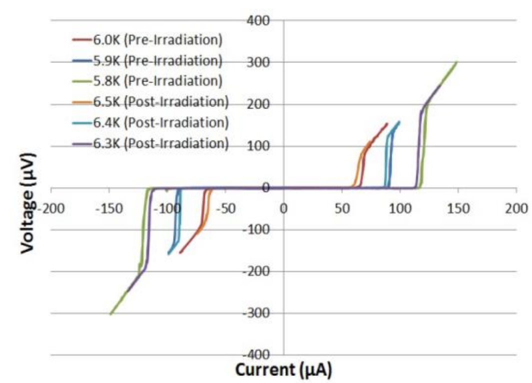




Chip :
about 5x5 mm^2

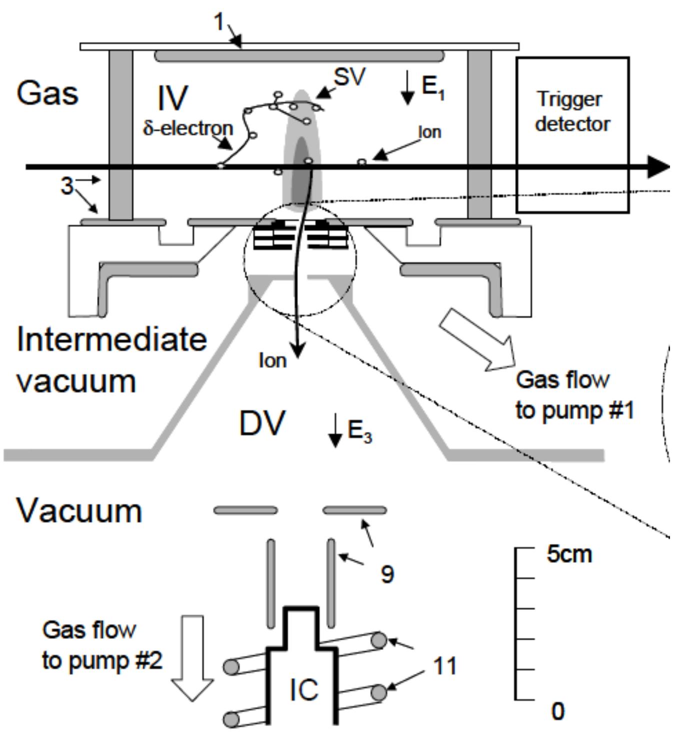
Andrea Pola, Politecnico di Milano



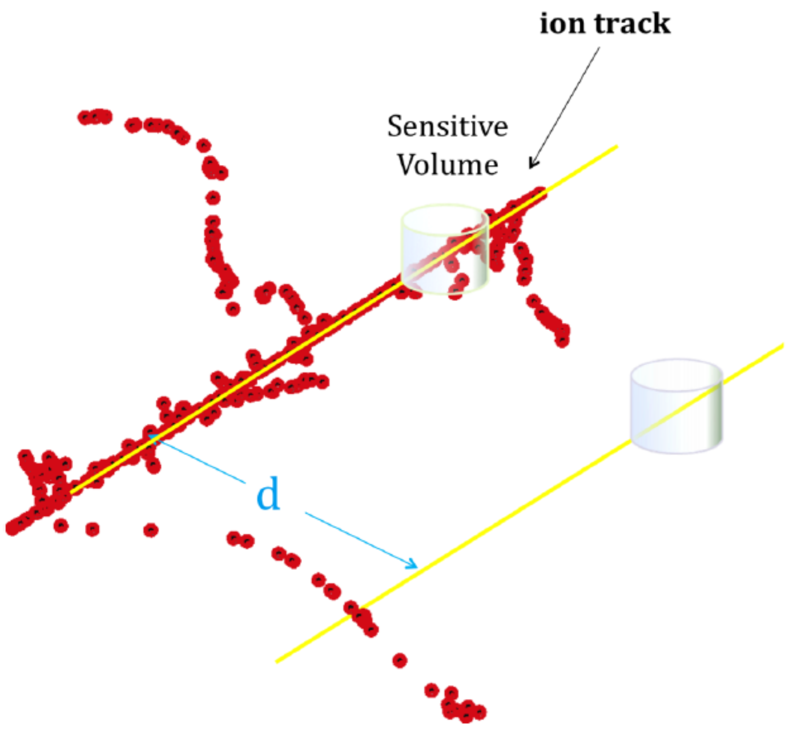


Seb Galer, NPL

Nanodosimetry…



Ion counter / PTB



Startrack / INFN

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